Pushing the limits of γ-ray spectroscopy of neutron-rich fission fragments with AGATA–PRISMA coupling

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In this Letter of Intent, we aim to study the structure of neutron-rich nuclei in the region of ^{78}Ni. The main focus is to investigate states resulting from the coupling between excited states of the inert core and valence protons in the $N = 50$ nuclei ^{79}Cu and ^{80}Zn. In addition, the proposed experiment will provide a systematic and relevant dataset on excited states in this region of the nuclear chart, extending the neutron-rich frontier by approximately two neutrons per atomic number compared to what has been achieved in previous studies with similar setup. The nuclei of interest will be produced via transfer- and fusion-induced fission reactions in inverse kinematics. The PRISMA spectrometer will be used to isotopically identify fission fragments, and the AGATA gamma tracking array will measure prompt γ rays.

I. PHYSICS MOTIVATION

The characterization of the nuclear structure of doubly-magic nuclei and their neighbors is of fundamental importance for understanding the nuclear force. The doubly-magic nature of nuclei has been established both experimentally and theoretically, primarily near the valley of stability, thereby establishing the classical magic numbers. In exotic nuclei, the persistence or disappearance of these classical magic numbers is the subject of intense ongoing experimental and theoretical investigations.

The Ni isotopic chain is unique in having three three experimentally accessible isotopes characterized by a classical double-shell closures ($N = 28$, 40 and 50). ^{78}Ni, marking the region of interest of this LoI, has the highest $N/Z \sim 1.79$ ratio making it one of the most experimentally challenging. Considerable experimental efforts have been devoted to studying nuclei in its vicinity [1–8], while the first experimental measurement of its structure was achieved at the RIKEN facility [9]. Although the doubly-magic nature of ^{78}Ni has been confirmed, theoretical calculations suggest the presence of a low-energy deformed structure, as shown in Fig. 1, and identify it as a possible turning point towards the disappearance of the $N = 50$ and $Z = 28$ magic numbers [9, 10].

In our recent work at GANIL in this region, the high-spin structure of ^{81}Ga ($N = 50$, $Z = 31$) has been investigated [13]. In Fig. 2, the newly obtained level scheme of ^{81}Ga is shown. The excited states up to $J^{\pi} = (11/2^{-})$ are interpreted as being mainly due to excitations of the three valence protons. States with higher spin require particle excitations across the magic gaps, originating from the ^{78}Ni inert core. The theoretical predictions are in excellent agreement with the experimental level scheme, highlighting the strong predictive power of this theoretical approach. The dominant configurations of the excited states are also given in Fig. 2. The states associated with inert-core

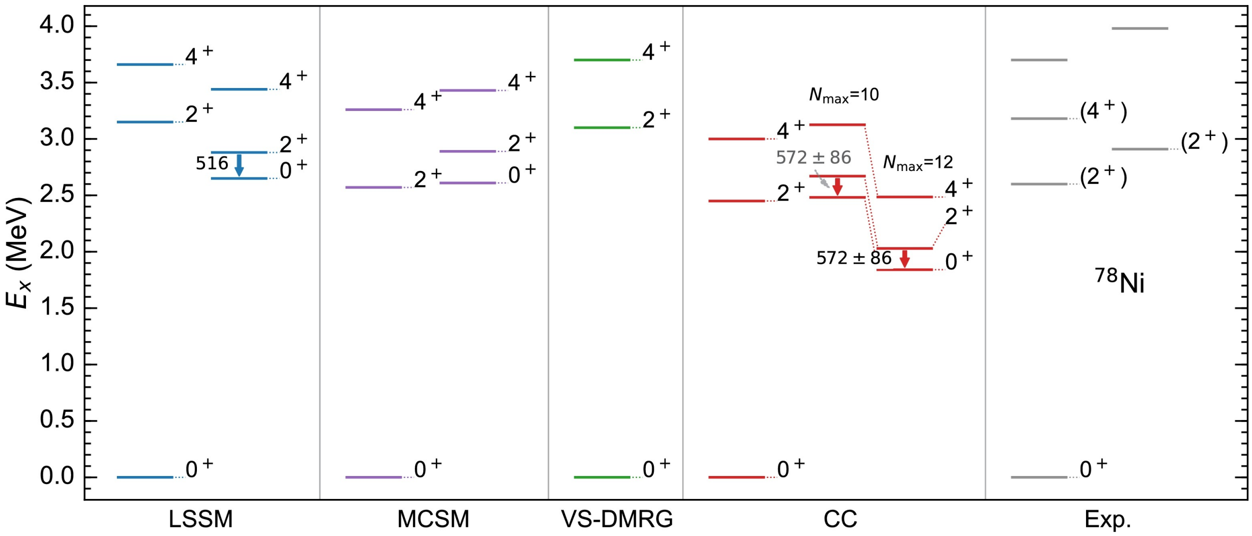

FIG. 1. Experimental level scheme of ^{78}Ni [9] compared to theoretical predictions. Theoretical results include the Large-Scale Shell Model (LSSM) [11], Monte Carlo Shell Model (MCSM) [9], Valence-Space Density Matrix Renormalization Group (VS-DMRG) [12] and ab initio coupled-cluster (CC) [10]. Figure taken from [10].

excitations of the inert-core are dominated by the $\nu d_{5/2} g_{9/2}^{-1}$ ($1p$–$1h$) configuration, and are in the same energy range as the measured states in ^{78}Ni (see Fig. 1).

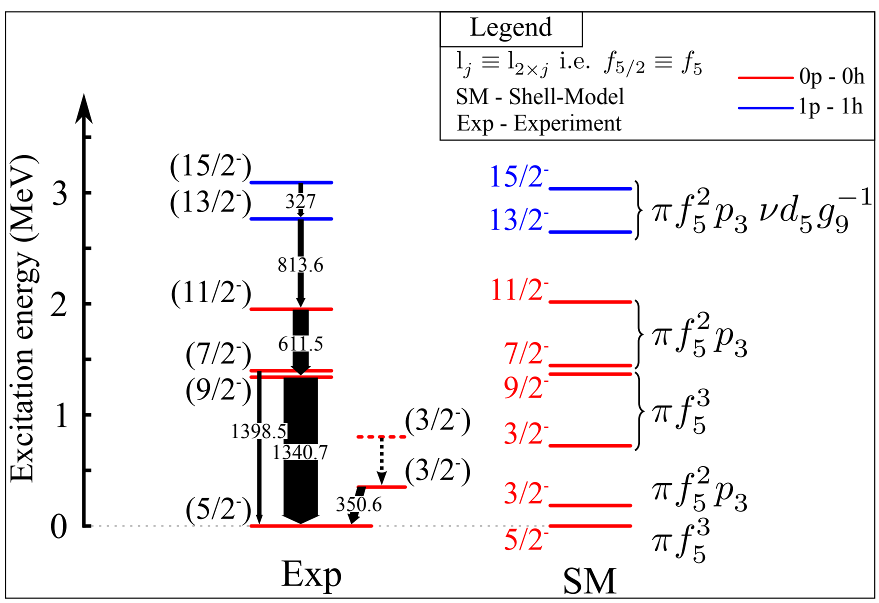

FIG. 2. Experimental and theoretical level scheme of ^{81}Ga [13].

While this work confirmed the possibility of extracting information on the ^{78}Ni inert core from less exotic $N = 50$ isotones, no experimental evidence of the deformed structure has been obtained.

This non-observation could be attributed either to the limited statistics available in this experiment, or to the fact that the deformed structure lies at too high an excitation energy in nuclei with three additional protons above ^{78}Ni.

Obtaining more experimental details on such deformed states in ^{78}Ni is technically too challenging today, but the less exotic $N = 50$ isotones above ^{78}Ni can provide valuable experimental data to probe the relevant structural features needed to constrain and improve the predictive power of theoretical models. In this work we propose to study nuclear states where a few valence protons are coupled to excitations of the ^{78}Ni inert core. These states, through the excitation of particles across the magic gap are intimately connected to the eigenstates of ^{78}Ni. Our joint experimental and theoretical effort will enhance our understanding of the evolution of states involving inert-core excitations and the impact of valence protons on the structure of these excitations.

Recent results in $N = 50$ isotones above ^{78}Ni

$N = 50$ isotones above ^{78}Ni have been the subject of intensive experimental effort in the last decade:

- ^{82}Ge has been studied via βn decay [14], Coulomb excitation [15], proton knock-out reactions [7], spontaneous fission [16, 17], deep-inelastic collisions [18] and more recently via neutron-induced fission [19]. The latter work reported levels with spins tentatively assigned up to (7^+), interpreted as a $N = 50$ core-breaking state.

- ^{81}Ga has been studied in β-decay [20–22] where low-lying proton states were reported. Some of these transitions correspond to those observed in our work [13] (Fig. 2).

- ^{80}Zn has been investigated via Coulomb excitation [4] and recently by via proton knock-out reactions [7]. The low-lying levels have been reported (2^+, 4^+), but no high-spin core-excited configurations have been identified. A recent high-precision mass measurement observed the presence of a low-lying isomer in ^{79}Zn, interpreted as the band-head of a low-lying deformed structure pointing to shape coexistence in ^{79,80}Zn, similarly to what is predicted in ^{78}Ni [23].

- ^{79}Cu has been investigated via proton knock-out reactions [8]. The level scheme has been established up to $\sim$ 5 MeV, but only the first excited state has been tentatively assigned. A multiplet of states around 3 MeV is interpreted as a core-excited configuration, although they could not be individually identified.

Complementarity of nucleon knock-out and fission

Proton knock-out reactions and fission are expected to populate different states and can thus provide complementary spectroscopic information. On the one hand, single-nucleon knock-out reactions are highly selective, as they proceed via the removal of occupied single particle states of the projectile. The populated states can be either yrast or non-yrast, depending on the available orbitals, angular momentum selection rules, and the spectroscopic factor between the initial and final states. On the other hand, fission predominantly populates yrast states, regardless of their underlying structure. A typical entry point corresponds to spin values around $\sim 20\hbar$. Thus, in the proton knock-out to ^{80}Zn, yrast and near-yrast 2^+ and 4^+ states are mainly populated, while the direct population of neutron inert-core excitations remains out of reach. The spectroscopic information obtained from fission is therefore complementary to that obtained from knock-out reactions, in particular for probing states with dominant neutron core-excitation configurations.

Experimental goals

In the present LoI, we aim to investigate:

- the first excited states in ^{79}Cu,
- the evolution of core-excited states in ^{80}Zn and ^{82}Ge by measuring states with $J \geq 6^+$ and $J \geq 8^+$, respectively,
- the possible appearance of the deformed structure predicted in ^{78}Ni in $N = 50$ isotones,
- the spin determination of known, strongly fed states using γ-ray angular correlations (in particular in ^{81}Ga and ^{82}Ge).

In addition to these specific physics cases, it should be noted that the proposed experiment will provide sufficient statistics to extend the neutron-rich frontier of the identified nuclei by approximately two neutrons per atomic number, compared to what has been achieved in previous studies. This will significantly increase the number of nuclei for which new spectroscopic information can be obtained. The studies that we have published from the previous AGATA–VAMOS++ coupling at GANIL on Kr [24], Br [25], As [26], Ga [13], and Zn [27] will thus be extended to higher spins and more neutron-rich nuclei.

II. EXPERIMENTAL METHOD AND SETUP

We propose to use an experimental approach similar to that employed in the E680 experiment, which used AGATA and VAMOS++. Previous studies carried out at GANIL have demonstrated that very neutron-rich nuclei can be populated via transfer- and fusion-induced fission reactions in inverse kinematics. Figure 3 shows the typical range of nuclei populated in fission, in coincidence with γ-rays, as measured in the E680 experiment.

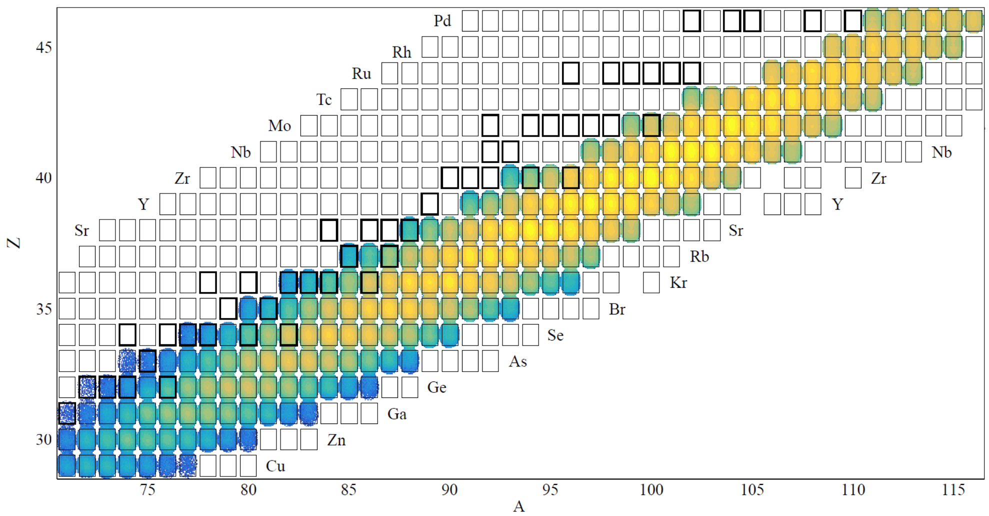

FIG. 3. Segré chart of nuclei populated in fission and detected in coincidence with γ-rays in the E680 experiment.

Prompt γ-ray spectroscopy, including γ–γ coincidence measurements, was performed during this 14-day experiment. Among the many neutron-rich nuclei populated, detailed spectroscopic results have been published for $^{99\text{–}109}$ Nb [28], ^{104}Nb [29], ^{96}Kr [24], $^{87\text{–}93}$Br [25], $^{83\text{–}87}$As [26], ^{81}Ga [13], and $^{73\text{–}75}$Zn [13].

As an example, Fig. 4 shows the tracked γ-ray spectrum obtained for ^{81}Ga, which lies three protons above ^{78}Ni. Five new transitions were identified, and a new level scheme was deduced (see Fig. 2). Table II summarizes the number of isotopically identified fission fragments detected in coincidence with prompt γ-rays for a selection of nuclei. The feasibility of the proposed experiment relies on the measured rates from E680 and the improvements in the detection system listed below.

A ^{238}U beam at 7.2MeV/u will impinge on a ^{9}Be target (15μm thick). The experimental setup will consist of PRISMA (positioned at 26°) coupled to the AGATA γ-ray tracking array. Fission fragments will be identified on an event-by-event basis, and prompt γ-rays will be detected with AGATA, operated in compact configuration and equipped with absorbers to reduce the counting

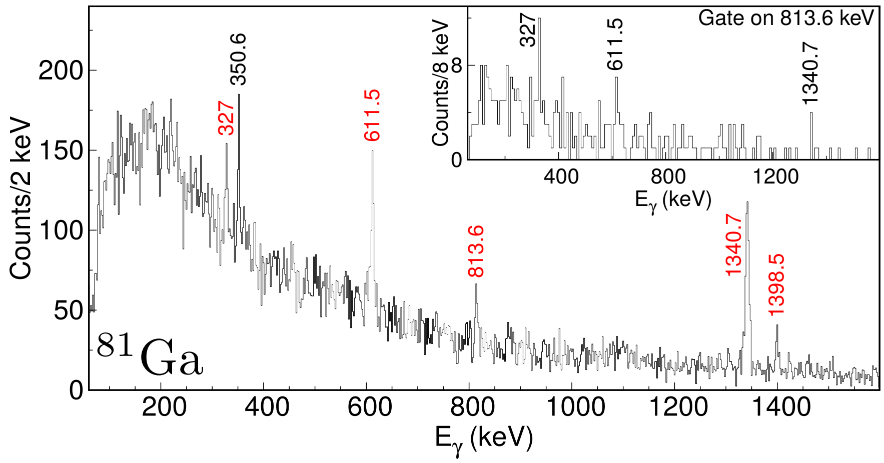

FIG. 4. Tracked γ-ray spectrum measured with AGATA in coincidence with isotopically identified ^{81}Ga fission fragments. The inset shows the spectrum gated on the 813.6 keV transition.

rate from uranium X-rays.

The proposed experimental setup offers a significant improvement in performance compared to the E680 experimentl:

1. The bulk of the phase space of interest is concentrated in a region where PRISMA covers approximately **90%** of the acceptance of VAMOS++.

2. Thanks to the higher counting rate capability of PRISMA, the target thickness can be increased from 10 to 15 μm, resulting in a gain of **1.5**.

3. A beam current of 1 pnA will be used, compared to 0.8pnA at GANIL, resulting in a gain of **1.25**.

4. For the estimated counting rate in PRISMA (3.75kHz), the dead time (including detection inefficiency) has been measured at 40% (17% of readout dead time, 80% of MCP efficiency, 90% of typical tracking reconstruction), compared to 50% with VAMOS in the GANIL experiment, resulting in a gain of **1.2**.

5. Due to trigger processor limitations during the GANIL experiment and the limited number of AGATA detectors available at the time, the single-detector efficiency was measured to be approximately 2% at 1 MeV. With the proposed setup, composed of 33 AGATA crystals, the single-detector efficiency has been measured at 6.5% at 1 MeV, resulting in a gain of **3.2**. The gain in γ–γ coincidences will also be significantly increased.

In the present proposal, we request 30 days of beam time, compared to the 14 days allocated for the GANIL experiment. Taking into account the improvements described above and the increased beam time, an overall gain of approximately **13** is expected. This beam time includes one day (three 8-hour shifts) dedicated to source measurements, which will be used to monitor the stability of the detection system over time. A detailed summary of the corresponding experimental parameters and expected gains is provided in Table I.

Parameter	**AGATA–VAMOS**	**AGATA–PRISMA**	**Gain**
Beam	^{238}U @ 6.3 MeV/u 25 enA (0.8 pnA)	^{238}U @ 7.2 MeV/u $\sim$1 pnA	**1.25**
Target	^{9}Be, 10 μm (1.85 mg/cm^2)	^{9}Be, 15 μm (2.77 mg/cm^2)	**1.5**
Fragments detection	2 kHz trigger, 1 kHz validated $\rightarrow$ 50%	3.7 kHz trigger read out + reconstruction $\rightarrow$ 40%	**1.2**
AGATA configuration	24 crystals Compact (14 cm from target) $\sim$2% at 1 MeV	33 crystals Compact (18 cm from target) 6.5% at 1 MeV	**3.2**
Beam time	14 days	30 days (including 3×8h of source runs)	**2.1**
Acceptance	$\Delta\theta \pm 6°$, $\Delta\phi \pm 10°$	Geometrical inefficiency (10%)	**0.9**
Total			**$\sim$13.4**

TABLE I. Comparison of experimental configurations and expected gain between AGATA–VAMOS (E680) and the proposed AGATA–PRISMA setup.

Based on the measured rates of isotopically identified nuclei in coincidence with prompt γ-rays from the E680 experiment, and taking into account the improvements described above, the expected rates for ^{82}Ge, ^{81}Ga, ^{80}Zn, and ^{79}Cu can be estimated and are summarized in Table II. From the E680 experiment analysis, it has been determined that with approximately 10^3 events, single γ-ray spectroscopy becomes feasible — for instance, the $2^+ \rightarrow 0^+$ and $4^+ \rightarrow 2^+$ transitions in ^{80}Zn were observed. In contrast, with about 10^4 events, γ–γ coincidence data can be extracted, as demonstrated for ^{81}Ga and ^{96}Kr. Given the higher expected statistics for ^{82}Ge and ^{81}Ga, spin determination using γ-ray angular correlations should be achievable.

In conclusion, we propose to perform high-resolution γ-ray spectroscopy of high-spin states in the neutron-rich nuclei ^{82}Ge, ^{81}Ga, ^{80}Zn, and ^{79}Cu, along with spin assignments of the most strongly populated states via γ-ray angular correlation measurements. These specific nuclei have been selected to illustrate the core objective of this proposal: probing the structure of $N = 50$

Nucleus	E680	Expected rate
^{96}Kr	2×10^4	2.6×10^5
^{82}Ge	3×10^5	3.9×10^6
^{81}Ga	4×10^4	5.2×10^5
^{80}Zn	2×10^3	2.6×10^4
^{79}Cu	1×10^2	1.3×10^3

TABLE II. Total number of isotopically identified fission fragments in coincidence with prompt γ-rays measured in the E680 experiment and expected rates for the proposed setup.

isotones just a few protons above the doubly-magic ^{78}Ni, in order to explore the coupling of valence protons to excitations of the inert core and search for possible deformed structures.

However, the experimental approach we propose naturally provides access to a much wider variety of fission fragments. As demonstrated by the extensive dataset collected during the E680 experiment at GANIL, such a configuration allows for the identification and spectroscopic investigation of a large number of neutron-rich nuclei across a broad range of atomic numbers. The improved performance expected in the present setup will significantly enhance statistics and detection sensitivity, enabling detailed studies of many other isotopic chains beyond the $N = 50$ line.

We therefore emphasize that, while the discussion in this Letter of Intent is centered on the physics cases around ^{78}Ni, the experiment will provide high-quality data suitable for the construction of level schemes, spin/parity assignments, and structure interpretations for a wide range of exotic nuclei. This makes the proposed experiment a versatile and valuable opportunity for advancing nuclear structure studies well beyond the examples detailed here.

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